Coordinating soil and rock material in urban construction — Scenario analysis of material flows and greenhouse gas emissions

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ABSTRACT

Construction is associated with quarrying as well as heavy transportation of soil and rock materials, in and out of construction sites. Both quarrying and transportation of the excavated materials result in negative environmental impact due to energy use and greenhouse gas (GHG) emissions. Moreover, soil and rock materials of suitable geotechnical quality for construction are a scarce natural resource in some urban regions. These issues have urged the need to optimize the use of quarry materials on-site and thereby reduce transportation. Still, internal flows of soil and rock materials in urban areas have not been well analyzed. This study presents a model to analyze future soil and rock flows in terms of material quality and quantities in urban areas. Furthermore, the study analyses the possibility of recycling excavated soil and rock and thereby reduce transportation and transport-related GHG emissions. The study applies the model in a case study to analyze integrating future residential and non-residential developments and a highway project. The case study revealed that excavated material would be generated in enough volumes to potentially cover the quarry materials demanded for providing stability and permeability to buildings, streets and highway. The scenario analysis showed that provision of strategically located recycling sites for material coordination could reduce the demand for soil and rock transportation as well as transport-related GHG emissions i.e. by 23–36% per area, compared to a business as usual scenario. The study shows that internal soil and rock flows within regions can be modelled by using data from development plans and geological maps. The model results may serve as a basis for decision making regarding strategic material management in urban planning.

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1. Introduction

Construction involves management of soil and rock materials. These materials are generally excavated and prepared for houses, roads and other civil engineering purposes. Soil and rock materials from quarries or excavated from other construction sites are also used for e.g. filling, permeable layers, base layers, landscaping and as filler in concrete and asphalt. Construction work involves quarrying as well as frequent heavy transportation of soil and rock materials, in and out from the construction sites. Both quarrying and heavy transport give rise to negative environmental effects in terms of energy use and greenhouse gas (GHG) emissions. Moreover, soil and rock are natural resources. In regions with lack of space and limited availability to quarry material, resource efficiency is of great importance. Nevertheless, excavated soil and rock materials are extensively landfilled. For example, annual landfilling of excavated soil and rock can range from 0.4 to 5.5 tons per capita (Rosado et al., 2014; Forsman et al., 2013) and quarry extraction from 4.6 to 8.0 tons per capita (McEvoy et al., 2004; Hiete et al., 2011). This clearly indicates the importance of improved industrial symbiosis and material management. In this context, recycling excess materials in order to reduce quarry extraction can be considered as a solution (CLaire 2013). It can contribute to a decrease in energy use and GHG emissions from both quarrying and transportation. Past empirical studies have shown the geotechnical and geo-environmental potential for replacing quarry materials with recycled materials such as soil and rock, brick, glass, etc.
about 7.7 kg of CO2 equivalents per ton. The positive effect of recycling materials in reducing transport-related GHG emissions have been supported by previous studies. For example, the emission savings by recycling could be 2.4 kg CO2 equivalents/ton material, according to a case study in England (CL:aire 2013) and 4 kg CO2 equivalents/ton material according to a case study in Finland (Säynajoki et al., 2018).

In order to improve material coordination and recycling possibilities between construction sites, it is important to provide soil and rock recycling sites that are located relatively close to each other (Hao et al., 2007). The life span of such sites can vary. Quarries are likely to have life spans of decades while other sites can be created temporarily within a construction site. The appropriate location for the recycling sites depends on different factors such as supply and demand for soil and rock materials, transportation distances, land occupation as well as costs. The appropriate localization of recycling sites has been assessed by Robinson and Kapo (2004). In their study, demand for aggregates in construction and information from recycling industry of asphalt and concrete, was used to choose locations that are most suitable at the state level of Virginya, USA. Galan et al. (2013) assessed optimized localizations for construction and demolition waste in the region of Cantabria in Spain focusing on concrete, mortar and ceramic.

Huang & Hsu (2003), McEvoy et al. (2004), Rosado et al. (2014) calculated soil and rock material flows in urban regions based on waste and construction statistics. A literature review by Magnusson et al. (2015) revealed that recycling of soil and rock is often hindered by the lack of overview of both quality and quantity of soil and rock materials on a regional scale at the early stage of the planning process. Information about the need for soil and rock materials is generally not available at the early stage of planning but provided in the implementation phase of each single construction project. In this paper we complement previous studies of urban metabolism and waste management by offering a more detailed description of future material quantities and qualities demand. This study employs the model developed within the research program “Optimass” to calculate soil and rock flows (for more information, visit www.optimass.se). The model considers future need for excavations and demand for filling materials for houses and streets. Equations for excavation need and filling demand was developed for different house types (Israelsson, 2014) and a model was subsequently developed for analyzing material flows between construction sites and recycling sites as well as transportation need and related GHG emissions.

This study builds on previous academic work related to Project Optimass - an initiative established by Stockholm-based Ecoloop AB that specializes in effective and efficient materials management in the construction industry. This study aims to assess the environmental benefits of material recycling in an urban area using the Optimass model for soil and rock flows in the region of Södertörn in Stockholm, Sweden.

The objectives of the study can be summarized as follows:

i) present the Optimass model and apply the model to analyze soil and rock material qualities and quantities resulting from excavations and fillings in future residential and non-residential building developments within the Södertörn region of Stockholm, Sweden;

ii) analyze regional self-sufficiency regarding soil and rock materials;

iii) analyze changes in material efficiency, transportation demand and corresponding GHG emissions by comparing a business as usual scenario with a soil and rock coordination scenario.

2. Material and methods

2.1. Methodology overview

An urban area in Stockholm, Sweden was selected as our case study. The area is part of the Södertörn Region and includes three municipalities, where each entity is planning for several new districts. Development plans involve mainly new residential buildings but also non-residential buildings such as industrial sites and commerce. A new highway, Tvärforbindelsen Södertörn, will be constructed and runs through the area of the case study, connected by tunnel sections. In this study, the Optimass model was used for calculating quantities and geotechnical properties of soil and rock generation and demand within residential and non-residential construction. For the highway project, data for geotechnical properties and quantities of soil and rock material was gathered from the Swedish Transport Administration. For the scenario analysis the studied area was divided into four areas where the potential for soil and rock coordination was analyzed separately. Each of the four areas holds several developing areas and a section of the highway. The study results were shared with project leaders of the highway and development managers and planners from the municipalities. The results were then used as a basis for finding appropriate locations for recycling sites.

2.2. Case study of the Södertörn Region

The location of the Södertörn Region is presented in Fig. 1. The area is a peri-urban area in the south of Stockholm with about 280,000 inhabitants. The area has both denser parts with multi-residential houses and industry/commerce. The cityscape is characterized by both groups of multifamily houses less than 10 floors and detached/semi-detached family houses. The central part has green areas. New residential and non-residential buildings are mostly planned in existing urban areas. The population is expected to increase by 41,000 people between year 2020–2030. The 17.7 km long highway will connect the area from southeast to northwest. In order to reduce traffic disturbance and negative environmental impacts of road construction, the construction of a 7 km tunnel in the northeastern part has been considered. The highway is expected to be completed by year 2030.

2.3. The studied system

The studied system included the material flows arising from transportation of soil and rock materials to and from construction activities within the region. Fig. 2 displays the conceptual model which is a simplified version of the model developed by Magnusson et al. (2015). In their study soil and rock was transported through the system without considering construction sites, recycling sites or landfills. Such flow is connected to construction activities outside the area of the current study, and therefore ignored. Soil and rock materials are used in construction for different purposes, such as providing stability to buildings and as road base layers, protecting pipes and cables in trenches, providing water drainage and filling voids. The demand of soil and rock materials can be met by either materials from quarries or excavated soil and rock with
suitable geotechnical properties. Excavated soil and rock materials can be reused within the construction developments. Excess materials can also be transported for either sorting or storage at so-called recycling sites before sending them to construction sites for recycling. Non-recyclable materials can be exported to landfills or other construction sites outside the studied system. In addition, soil and rock materials can be imported to the studied system (Magnusson et al., 2015).

In this study, estimation of quantities and qualities of soil and rock was based on material flows illustrated with arrows (Fig. 2). We divided the studied region into several areas, where each area incorporated a group of construction developments and a single recycling site. We analyzed the material balance between 2020 and 2030 for each area. Our analysis did not include the demand for materials used in construction activities above ground level such as asphalt for roads and concrete in house bodies.

This study analyzed two scenarios for management of soil and rock in the studied system, see Fig. 3. The scenarios included fill material and permeable layers for buildings and base layers for roads. Excavated rock, sand and gravel and till are relatively easy to prepare for recycling as fill, permeable layer or base layer. In Scenario 1, excess excavated rock, sand, gravel and till were sent away from the system for the sake of recycling or landfilling, while quarries provided materials to meet construction needs. In Scenario 2, excess excavations were transported to a locally established recycling site for storage and recycling. Both scenarios assumed that excess materials not needed for recycling, were exported from the system. This study does not consider soft or contaminated soils or clay for scenario analysis since they are more difficult to recycle in the relevant applications. This study compares the two scenarios in terms of material efficiency (m$^3$ of recycled material), transportation need (km) and GHG emissions from transportation activities (ton CO$_2$ equivalents) which includes loading and transportation of the materials. Internal operations for handling rock, sand, gravel and till at both landfill and recycling station may differ in terms of internal transportation, sorting, crushing, etc. Due to such uncertainties, it was assumed that these internal operations are the same in both scenarios. Thus, they were excluded from the scenario analysis.

For the scenario analysis, the case study area was divided into four areas (Fig. 1). Sections of the highway project was included in all four areas. The required data for the highway project, such as timetable for excavations and material demand was accessed from the Swedish Transport Administration. The data collection is described more in-depth by Miyaoka (2015).
2.4. Description of the soil and rock material flow model

2.4.1. Excavation in residential and non-residential developments

Construction of residential and non-residential buildings involves ground excavation for houses and infrastructure such as streets, pavements, parking lots, ditches, as well as telecommunications, water and sewage etc. The model consists of five equations where each equation represents the excavation need for different types of construction.

Equation (1) represents the volume for house excavation:

\[ V_{\text{house}} = \varepsilon \cdot \frac{GFA}{n_f} \cdot d \]  

where \( \varepsilon \) = excavation factor.

\( GFA \) = Gross floor area,
\( n_f \) = number of floors, and
\( d \) = excavation depth.

The excavation factor is defined as the ratio between the excavated area and the actual building area. The perpendicular distance between the outsides of house and excavation pit may fall between the range of 1.5 and 2.25 m (Israelsson, 2014). Depending on house size and its shape, the excavation factor may vary. The results of the numerical modelling for different house sizes with different perpendicular distances show that the excavation factor can range mainly from 1.35 to 1.54. When it comes to houses between 400 and 700 m², the excavation factor is reported as 1.4 (Israelsson, 2014).

Equation (2) represents the volume for street excavation:

\[ V_{\text{street}} = 17 \cdot l \cdot 0.7 \cdot \frac{GFA}{n_f} \]  

where \( l \) = length (street).

\( GFA \) = gross floor areas and
\( n_f \) = number of floors per building.

In this study, the width of street lane was set to 10 m, comparable with the work of Israelsson (2014) including trenches for electricity, telecommunications, water and wastewater, drainage, district heating and street parking and bicycle paths. Israelsson (2014) reported the excavation volume for streets as 17 m³/meter street. Israelsson (2014) also modelled the relationship between street length and actual building area. As presented in Eq. (2), the information from Israelsson (2014) enabled us to simplify the calculation for excavation needs for streets.

Equation (3) represents the excavation volume for parking lots below ground:

\[ V_{\text{parking lot}} = 75 \cdot n_a \cdot \alpha \cdot \beta \]  

where \( n_a \) = number of apartments.
\( \alpha \) = share of parking lots below ground,
\( \beta \) = share of parking lots per apartment.

Based on the requirements from the Swedish Transport Administration (2015) on road design, underground parking lot construction was calculated to require excavation of 75 m³ per parking lot. It is assumed that half of the underground parking space is located under houses. Therefore, excavation volumes for half of underground parking are already reflected in calculating house excavations i.e. Equation (1), accounted for by the “2” in the denominator of Equation (3).

The total volume of excavated material from residential areas is expressed in Equation (4):

\[ V_{\text{total excavation}} = V_{\text{house}} + V_{\text{street}} + V_{\text{parking lot}} \]

\[ = \left( \varepsilon \cdot \frac{GFA}{n_f} \cdot d \right) + \left( 0.7 \cdot \frac{GFA}{n_f} \right) + \left( 75 \cdot n_a \cdot \alpha \cdot \beta \right) \]  

The calculations were simplified for non-residential areas. It was assumed that the whole construction site is excavated to prepare for construction.

The excavated volume from non-residential construction is expressed in Equation (5).
\[ V_{\text{non residential}} = \frac{\text{GFA}}{n_f} \cdot d \] (5)

Information about residential and non-residential developments can be collected from municipal strategic development plans where population prognosis for municipalities is available. Information about the number of floors in buildings were collected either from municipal plans or by means of satellite photos in case of missing information.

2.4.2. Material demand in residential and non-residential developments and on-site reuse

Isaëllson (2014) suggested permeable layers placed beneath buildings and around basement to be 0.25 m thick (Isaëllson, 2014). Filling need was calculated as the difference between the excavated volume and the volume taken up by the body of the house and the permeable layer. Isaëllson (2014) also reported that for houses with an excavation depth between 2 and 4 m, the demand for permeable layers and filling is about 20% and 33% of the total excavation volumes, respectively. Material demand for streets was set to sand and gravel fraction (Isaëllson, 2014). Our study assumed that the material demands i.e. filling, permeable layer and base layer for constructing underground parking lots are insignificant. Therefore, they are not considered in the calculations. Table 1 displays the material demands and the priority order for recycled material.

The share of reuse within residential and non-residential construction sites is small due to insufficient storage space for the excavated materials. In this study, on-site reuse rates were estimated to 10% for rock, till and soft/contaminated soils. Regarding sand and gravel, the reuse rate was set to 0% since these materials are often requested and easily recycled in other construction projects with lesser effort for preparations e.g., sorting.

3. Calculations

3.1. Residential and non-residential developments

Information about residential developments was collected from municipal strategic development plans. Population growth data in different development areas of the studied region was collected from municipal sources. For residential areas, the excavation factor was set to 1.4. The number of parking lots per apartment was set to 0.8 according to the present municipal plans. The share of parking underground was set to 0.5. Information about the number of floors was collected from the municipal plans, when possible. Otherwise, it was assumed to be equal to the number of floors in existing buildings, ranging between 3 and 7. Floor levels in each area was analyzed by using satellite photographs. Average living area per person was set to 38 m² using data from Statistics Sweden (2018). Excavation depth was estimated to 4 m for all residential construction as reported by Isaëllson (2014). As for non-residential buildings, information related to Gross Floor Areas (GFA) was collected from municipal planning documents. The number of floors was estimated to be equal to surrounding non-residential construction, ranging from 1 to 6 floors. The excavation depth was set to 3 m for all non-residential construction.

Fig. 4 shows the results of a calculation example of contributions to excavation volumes from \( V_{\text{house}} \), \( V_{\text{street}} \) and \( V_{\text{parking}} \). In this example, a house with 70 apartment units, 2500 m² GFA and 5 floors was used as input in the calculations. The results show that about 80% of excavated volumes were due to house excavation and 10% were due to streets and parking lots below ground. Similarly, 80% of demanded soil and rock volumes were due to filling and permeable layers for houses and 20% for streets.

The selected study areas were envisioned by local municipalities to accommodate housing for new residential and non-residential developments by 2030, as quantified in Table 2. The population growth and GFA was collected from prognosis as presented in municipal comprehensive plans (Botkyrka, 2014; Haninge, 2016; Huddinge, 2014).

3.2. Highway construction

For this study, the highway is the only infrastructure project with noticeably larger excavation volumes. In Table 3, the section types for the highway in area 1–4 are specified. The presented data was gathered from the work of Miyaoka (2015).

Excess soil and rock materials and material demand for the highway was estimated by the Swedish Road Administration at the early stage and was gathered from Miyaoka (2015) and included in the calculations. Table 4 displays volumes of excess excavation divided in qualities and material demand divided in functions.

3.3. Excavated material types and recycling potential

For residential and nonresidential developments, it was possible to study the soil type mix at the locations by using detailed geological maps from Geological Survey of Sweden (2017). The dominating soil types in the studied region are shown in Fig. 5.

The quality of excavated soil and rock materials was assessed using soil maps for each construction site. The material qualities were classified into five categories, including i) rock, ii) sand and gravel, iii) till, iv) soft or contaminated soils and v) other low-quality materials.

Insitu density is the density of the untouched soil and rock materials with a natural degree of compaction and water content.

<table>
<thead>
<tr>
<th>Material demand</th>
<th>Material supply, priority order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill – houses</td>
<td>1) Rock</td>
</tr>
<tr>
<td></td>
<td>2) Sand and gravel</td>
</tr>
<tr>
<td></td>
<td>3) Till</td>
</tr>
<tr>
<td>Permeable layer – houses</td>
<td>1) Rock</td>
</tr>
<tr>
<td></td>
<td>2) Sand and gravel</td>
</tr>
<tr>
<td>Base layers – streets/highway</td>
<td>1) Sand and gravel</td>
</tr>
<tr>
<td></td>
<td>2) Rock</td>
</tr>
</tbody>
</table>

Fig. 4. An example of calculated contributions to excavation volumes of totally 3450 m³ and soil and rock material demand of 1834 m³ due to construction of a house with five floors and 2500 m² GFA.
The exsitu bulk density refers to the density of the materials after excavation and blasting. The compaction density is the density when materials are recycled and compacted for fill, permeable layer or other applications.

In Table 5, the insitu, exsitu and compaction densities for soil and rock materials are presented. They were calculated using swelling factors reported by www.engineeringtoolbox.com. In Table 5, “others” refers to materials with lower quality and density.

3.4. Transportation, loading and fuel consumption

Data regarding transportation distances for soil and rock materials by the recent studies of Lundberg et al. (2017) and Lundberg (2017) was used in the current study. They collected data by interviewing transporters and material suppliers within the Stockholm region. The results of interview data analysis show that rock, sand and gravel are often requested in other construction projects.

Fig. 5. Dominating soil types in the studied region. Maps from Geological Survey of Sweden (2017).
projects and is thus transported relatively short distances, whereas soft or contaminated soils are mostly sent further away for landfilling. With the increasing landfilling fees in the Stockholm region, transportation distance to the authorized landfills has shown an increase in recent years. Regarding Scenario 1 and 2, transportation distance for different materials are presented in Table 6. When it comes to Scenario 2, a recycling site was placed between several developments in order to reduce transportation distances. For each development project, transportation distances to recycling sites were specifically calculated. Recycling of soft or contaminated soils is likely to require more advanced preparation compared to rock, gravel, sand and till. In both scenarios, it is assumed that soft or contaminated soils are landfill. In Scenario 2, excess rock, sand, gravel and till are transported to recycling sites. At times when the material volumes at recycling sites exceed the demand, materials will cumulate. To avoid cumulation, it is likely that the material is further exported from the area and recycled outside the system. Transportation distances for exported materials are comparable to the transportation distances for excavated material types in Scenario 1.

Table 7 presents the average transportation distances from each individual construction site to recycling site in each area according to Scenario 2.

4. Model results and discussion

4.1. Soil and rock material flow in the region

Fig. 6 presents the modelled material flows in the case study according to the conceptual scheme of Fig. 2 as bulk volumes, i.e. excavated volumes. The model integrates all residential and non-residential construction activities in all four urban areas from 2020 to 2030. The highway construction is also included in the model. The estimated amount of excess soil and rock materials transported from construction developments are 8.93 million m$^3$. Remaining material demand is estimated to be about 3.88 million m$^3$, i.e. about 43% of excess material. A relatively large amount of excavated materials is associated with the highway construction. However, the residential and non-residential development areas account for the largest share i.e. 78% of total excess excavation volumes.

4.2. Material self-sufficiency in each area

Excess, demand and cumulated soil and rock materials in the four areas of the case study are presented in Fig. 7. The results show that local excess materials have the potential to address the total demand at each area, however, there would still be surplus materials cumulated in each area. Cumulating volumes are so large that there would be little possibility to locally store these materials. It is therefore assumed that they are sent away to other areas.

Table 5

<table>
<thead>
<tr>
<th>Densities for soil and rock material types.</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ton/m$^3$]</td>
</tr>
<tr>
<td>-------------</td>
</tr>
<tr>
<td>Rock</td>
</tr>
<tr>
<td>Sand, gravel and till</td>
</tr>
<tr>
<td>Soft or contaminated soil</td>
</tr>
<tr>
<td>Others</td>
</tr>
<tr>
<td>Fill</td>
</tr>
</tbody>
</table>

Table 6

| Transport distances, one way, for soil and rock materials in each scenario. |
|--------------------------------|------------------|------------------|
| Material quality               | Scenario 1 [km]  | Scenario 2 [km]  |
| Excavation                     |rock| 15          | 15   |
| Sand and gravel                | 20   | 20   |
| Till                           | 20   | 20   |
| Soft or contaminated soil      | 170  | 170  |
| Other                          | 50   | 50   |
| Quarry                         |rock, sand & gravel| 15     | 15   |

* Distance between each development site and recycling site is unique.

Table 7

Average transport distances from construction sites to recycling site in each area in scenario 2.

<table>
<thead>
<tr>
<th>Area</th>
<th>Distance, one way [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1</td>
<td>1.4</td>
</tr>
<tr>
<td>Area 2</td>
<td>0.7</td>
</tr>
<tr>
<td>Area 3</td>
<td>2.9</td>
</tr>
<tr>
<td>Area 3</td>
<td>4.7</td>
</tr>
</tbody>
</table>

Fig. 6. Model results; bulk volumes of soil and rock material flows (million m$^3$) in the region due to construction activities in the studied region, year 2020–2030.
The model results for material quality are presented in Fig. 8 with more details. The demand for fill, permeable layers and base layer within each area is considerably lower than the surplus materials, indicating the possibility of using excess rock from both residential and non-residential construction as well as the highway project.

4.3. Scenario analysis

The focus of this scenario analysis was exclusively on the management of rock, sand and gravel in each construction area. We excluded soft or contaminated soil or soils with a high degree of organic material from the analysis due to their poor geotechnical and/or environmental properties. The scenario analysis compares
the material efficiency, transportation need for the soil and rock materials and transport-related GHG emissions. Scenario 1 represents the current situation as a “business as usual” scenario, in which each construction project independently manages their soil and rock materials. Scenario 1 implies that each construction project is exporting most excavated soil and rock and using quarry materials to cover demands. In Scenario 2, soil and rock material are jointly coordinated between construction sites. Excess materials from each construction site is transported to a locally established recycling site where materials are stored and sorted, before recycling in other nearby construction developments. Included material qualities are soil, rock, sand, gravel and till. A low degree of on-site recycling is assumed in both scenarios. The material recycling/avoided quarry materials (ton), the transportation needs in terms of kilometers (km) and transport-related GHG emissions in terms of CO$_2$ equivalents (ton) in each scenario are presented in Figs. 9–11, respectively. The largest volumes of recycled material are achieved in area 3 and 4. This is primarily due to relative high construction rates and therefore high material demand. In area 3, about 52% of all residential developments will take place while area 4 holds about 49% of all non-residential developments. In scenario 1, transport-related GHG emission was highest in area 3, with about 44,000 ton CO$_2$ equivalents. In scenario 2, coordination of soil and rock materials resulted in a reduction of transportation and GHG emissions of 23–36% per area with largest savings in area 3. The savings in transportation and GHG emissions depends on recycling rates and transportation distances to recycling sites. However, transportation distances have large effects on the saving potential. For example, in area 2, recycling corresponded to only 82% of the volumes recycled in area 4. Still, CO$_2$ savings in area 2 was 76% higher than in area 4. This is a consequence of the relatively short transport distances to the recycling site in area 2, about 6.7 times shorter than in area 4, as seen in Table 7. The export of excess materials that otherwise would be cumulated in each area contributes to about 5.5%–18.1% of GHG emissions in Scenario 2, with lowest contributions in area 2 and highest contributions in area 4.

4.4. Sensitivity analysis

The material flow model enabled quantification of future soil and rock material flows in a region. However, the model required that many factors affecting excavation and demand of soil and rock materials are set to constant values if availability of site-specific data is limited. These factors are excavation depth, house design, and recycling rates within construction developments, among others. In order to reduce uncertainties, calculations could be refined when more specific data for construction developments is

![Fig. 9. Recycling of soil and rock/avoided quarry materials use within area 1–4 respectively in Scenario 2, compared to Scenario, 2020–2030.](image)

![Fig. 10. Transportation need of soil and rock in Scenario 1 and 2, 2020–2030.](image)

![Fig. 11. Transport-related GHG emissions for soil and rock material in Scenario 1 and 2, 2020–2030.](image)
available. Calculation results were analyzed regarding sensitivity to change of three parameters; excavation depth, number of floors and share of parking lots below ground. Fig. 12 displays the results from the sensitivity analysis of a residential development site in area 3. Average values for number of floors was set to five. House excavation depth and share of parking lots above ground was set to 4 m and 50% respectively. Average values were changed +/−25%. The sensitivity analysis showed that $V_{\text{house}}$ is sensitive to number of floors and excavation depth while the changes in $V_{\text{street}}$ and $V_{\text{parking lot}}$ are less significant. The sensitivity analysis highlights the importance of accurate information regarding floor levels. The sensitivity is largest for houses with few floor levels while the sensitivity is reduced with increased floor levels. A 25% decrease in number of floor levels, from 5 to 3.75 resulted in an increase of $V_{\text{house}}$ by 33%. A corresponding increase in floors levels decreased $V_{\text{house}}$ by 20%. The value of $V_{\text{house}}$ is linear to change in excavation depth. There is some dependency between floor levels and excavation depth. High houses might require larger excavation depth to be able to provide enough stability. In addition, soils with insufficient geotechnical properties may require even deeper excavation. However, excavation depth is usually limited due to costs. There will be a point where in situ treatment methods such as cement column stabilization will be more favorable than excavation and filling.

Depending on geological conditions, the uncertainties of results may vary. In areas with little changes in geology, excavation depths may be easier to estimate than in areas with large variations of soil and rock quality. In addition, when using average input values, analysis of single construction projects is likely to deviate far more from reality than when analyzing a multitude of projects.

4.5. Comparison with previous studies

Previous studies by Huang & Hsu (2003), McEvoy et al. (2004), Rosado et al. (2014), analyzed soil and rock material flows in urban regions. They use both waste statistics and construction statistics. The main research interest of these previous studies centered around the overall metabolism with a strong focus on input of quarry materials and output in terms of disposal to landfills. The model presented in this paper can complement previous studies of urban metabolism and waste management by offering a more detailed description of material quantity and quality demand, based on plans for future construction rather than waste statistics and construction data. A study by Choi et al. (2017) presented a model for economic analysis of soil and rock trading between construction sites. The economic model can be applied to construction developments where there is information regarding excess and demand for soil and rock materials. Often, such information is available only for projects to be started within a short time frame. The model in this paper could be used as a basis for similar more general economic analysis but in an earlier planning stage and including more construction developments.

The model results can be compared with previous studies on demand for quarry materials and generation of soil and rock in other urban areas. In the studied area, our model predicts excess excavated soil and rock to about 8.9 million m$^3$ during year 2020–2030, with an annual excess excavation per capita of about 3 m$^3$/year. Magnusson et al. (2015), showed that data on generation of excavated soil and rock in urban areas are scarce, but existing studies report amounts from 0.36 to 5.5 tonnes. Assuming a bulk density of 1.5 ton/m$^3$, it would correspond to 0.24−3.67 m$^3$ per capita and year. The results from our calculations regarding excess excavations in urban areas are therefore within the range of previous studies.

The GHG emission savings achieved in Scenario 2 can be compared with results from previous studies. In area 3 the recycling site allowed recycling of totally 0.84 million m$^3$. The transport-related GHG emission savings in area 3 was about 16,000 ton, about 19 kg CO$_2$ equivalents/m$^3$. In a previous case study by CLaIRE (2013) the use of local recycling sites allowed recycling of about 30 000 m$^3$ and reduced transport-related GHG emissions by 167 tonnes CO$_2$ equivalents. This correspond to a reduction of GHG emissions by 5.6 kg CO$_2$ equivalents/m$^3$ recycled material which is less than a third of the calculated savings in our study. The differences may be a consequence of the longer transportation distances (up to 52 km) to recycling site in the case study by CLaIRE (2013).

4.6. Further studies

The presented model could be further developed to also consider a wider perspective where production of quarry materials and activities on recycling sites are included. Such an approach would make it possible to analyze different management scenarios and material preparation methods. Depending on demand and soil

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**Fig. 12.** Sensitivity analysis of excavated volumes (m$^3$), for a residential development site in area 3.
qualities in a specific region, different recycling technologies are possible. There is a risk that some recycling practices involve activities that will reduce or eliminate the overall GHG emission savings from reducing transportations (Krantz et al., 2017). Further studies are therefore recommended not only to consider changes in transport-related emissions but also changes in other activities such as operation in quarries and at recycling sites. Such an approach would eliminate the risk for sub optimization when making decisions for management strategies.

To minimize conflicts between different stakeholder, it may be possible to establish temporary recycling sites that can be relocated. In this study, the construction of a highway will occupy space for several years before the highway is completed. The space may be used as a temporary recycling site. For example, areas where soils require preloading before construction, could serve as material storage and preparation. Such multifunctionality may be beneficial for both the highway project and for other surrounding developments. Such analysis would also require more detailed information about material quality and volume fluctuations in demand and excess and which capacity is required to manage volume peaks at the recycling site.

The presented model has been developed for analyzing material flows in clusters of construction projects, not in single construction projects. There is generally a conflict between collecting detailed construction information and the ability to strategically plan soil and rock management. The closer to the construction phase, the more information about building design and geotechnical properties can be collected. However, strategic planning might then be too late. Other ways of collecting information about soil and rock generation and demand can be through interviews with transporters and material suppliers or by collecting waste statistics or material balances from single construction projects. Annual excavated and demanded volumes can then be related to annual construction in the studied region and predictions for future construction developments can be made. However, this approach will require more input information from other actors and is limited to the knowledge of these individual actors.

The presented model in this study could be used as basis for strategic material management, for example, by pinpointing areas where construction developments would benefit the most from a recycling site. Uncertainties about actual excavation volumes and demand can be reduced by refining input parameters when more detailed information about construction developments are available as the urban planning moves forward, such as number of floors in residential blocks and geological information from field studies. Uncertainties about transport-related GHG emissions can be reduced by using more detailed information on lorry capacities, fuel consumption, transport distances to quarries, and landfills etc.

The study results were shared with the project leaders of the highway and development managers and planners from the municipalities. The results were helpful in identifying appropriate areas for recycling sites and for initiating a process towards enabling such sites. It is helpful if such process starts at the early stage, by including recycling sites in municipal comprehensive plans (Lundberg et al., 2017).

5. Conclusions

The Optimass model was presented and successfully applied to analyze future soil and rock flows in terms of material quality and quantity in urban areas. A case study of future residential and non-residential developments and a highway project in a peri-urban area south of Stockholm was carried out. The case study showed that excavated material will be generated in volumes enough to potentially cover a large share of the quarry materials demanded for fill, permeable layers and base layers. In the scenario analysis, the establishment of strategically located recycling sites for material coordination was shown to potentially reduce soil and rock transportation needs and hence transport-related GHG emissions by 23–36% per area, compared to a business as usual scenario. The results were shared with project leaders, development managers and planners as a basis for identifying appropriate locations for recycling sites. From the scenario analysis it was possible to identify the areas with the largest environmental potential for recycling sites. Sensitivity analysis showed that the number of floor levels as well as excavation depths significantly affect the model results. Therefore, it is recommended to use as accurate data for floor levels as possible, especially for residential developments, in cases with relatively few numbers of floors. There is a risk that some recycling technologies involve activities that will reduce or eliminate the overall GHG emission savings resulting from reduced transportation. Further studies are therefore recommended not only to consider changes in transport-related emissions but also changes in other activities such as operation in quarries and at recycling sites. The study shows that future internal soil and rock flows within regions, which has not been well explored in material flow analysis, can be modelled by using data from development plans and geological maps. The model results may serve as a basis for decisions on strategic material management in urban planning.

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